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BALANCE FOR MEASURING SKIN FRICTION IN THE PRESENCE OF HEAT TRANSFER

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10 JUNE 1969

NOL

UNITED STATES NAVAL ORDNANCE LABORATORY, WHITE OAK, MARYLAND

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BALANCE FOR MEASURING SKIN FRICTION IN THE PRESENCE OF HEAT TRANSFER

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ABSTRACT: The development of a skin-friction balance to be used in a wind tunnel with heat-transfer conditions is described. The balance is a null-type device with a floating head element whose temperature can be maintained between 100°K and 345°K. This is accomplished with a cooled or heated jacket that is placed in direct contact with the friction element. At the desired element temperature the jacket is separated from the element and the shear-force data is taken. The balance was used in a Mach 5 supersonic flow with moderate heat-transfer rates. Shear forces ranging from 0.05 gm/cm^2 to 1 gm/cm^2 have been measured and higher ranges can be obtained by simply changing a coil spring.

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Balance for Measuring Skin Friction in the Presence of Heat Transfer

This report presents a description of a device for directly measuring skin friction in the presence of heat transfer. This balance is being used extensively for making fundamental skin-friction measurements in supersonic turbulent boundary layers.

The authors wish to thank Messrs. F. W. Brown, F. C. Kemerer, and R. C. Sullivan for the efficient operation of the facility and preparation of the instrumentation.

The authors gratefully acknowledge the cooperation of E. Keener of NASA, Ames, who provided the uncooled balance for comparison with the present NOL balance.

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E. F. SCHREITER
Captain, USN
Commander

L. H. Schindel
L. H. SCHINDEL
By direction

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ILLUSTRATIONS

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INTRODUCTION

In the field of fluid mechanics, accurate measurements of the skin-friction drag are very important. The most direct way of making this measurement in a wind tunnel is with a skin-friction balance. Simulation of actual flight conditions in a ground facility needs the duplication of certain dimensionless parameters, called similarity parameters. One of these parameters for heat-transfer simulation is the ratio of wall temperature to free-stream stagnation temperature T_w/T_o. In free flight this parameter has values ranging from unity to 0.1 or less. Consequently, simulation in wind tunnels, where T_o has a value of 1200°K or less, it is necessary to cool the wall temperature of the model to much lower than room temperature in order to maintain the required range of T_w/T_o. The balance described in this paper is capable of using liquid nitrogen to achieve wall temperatures down to 100°K.

BALANCE OPERATION AND DESCRIPTION

The Naval Ordnance Laboratory (NOL) skin-friction balance (Fig. 1) is a null-type device in that deflections of the sensing element or friction element due to air loads are reduced to zero by a servodrive mechanism. The shear force causes the balance arm to rotate by an amount proportional to the magnitude of the shear stresses on the surface of the element. Movement of the balance arm is sensed by a translational Linear Variable Differential Transformer (LVDT). The LVDT is electrically excited by a 5-kHz, 5-volt signal from a Pace modulator-demodulator unit. The LVDT is attached to the balance housing while the transformer core is attached to the balance arm. Movement of the balance arm thus produces a differential voltage across the output terminals of the transformer. This differential voltage is then converted into a two-phase ac voltage and fed to the servomotor. Torque is transmitted from the servomotor and across a gear train to the lead screw as shown on Figure 2. The spring guide moves along the lead screw as it rotates. The linear motion of the spring guide and the balance arm. The force of the spring acts to restore the balance arm to a null position. A potentiometer is geared to the servomotor to provide an analog record of the balance arm deflection.

The Flexure

The balance arm is supported and pivots on two frictionless bearings called flexures. The flexure not only serves as a bearing, but also provides stiffness against the balance arm rotation.

The flexure core is a one-piece unit consisting of an outer ring with four web-like beams cantilevered from the ring and joined at a shaft in the center of the unit (Fig. 3). The flexure is made

from a single piece of stainless steel by an electrical discharge machining method. The rotational stiffness of the shaft with respect to the ring is a function of the bending stiffness of the flexures. The mode of bending a single flexure is analogous to the case of a rectangular beam with one end fixed and the other end simply supported where a moment M_o is applied at the simple supported end (Ref. 1). The slope θ at the simply supported end is given by:

$$\theta = \frac{M_o \ell}{4EI}$$

where ℓ is the length of the beam, E is the modulus of elasticity a and I is the moment of inertia. The stiffness of the beam is defined by

$$k = M_o/\theta = 4EI/\ell$$

For the case of the four flexure units

$$k = 16EI/\ell$$

The moment of inertia of the beam for width b of 0.254 cm and thickness t of 0.0173 cm is

$$I = bt^3/12 = 1.09 \times 10^{-7} \text{ cm}^4$$

The stiffness of the beam with $E = 32.9 \times 10^6$ kg/cm^2, $\ell = 0.762$ cm is

$$k = 5.72 \text{ cm-kg/rad}$$

A damping unit, which is contained within the flexure housing (Fig. 4), was developed by Durgin (Ref. 2). The unit consists of a damping wheel attached to the flexure shaft, and is sandwiched between two stationary disks. The gaps between the damping wheel and the stationary disks are filled with a damping fluid (500,000 centistoke silicone oil) which retards the relative motion between the wheel and disks.

Balance Cooling

The NOL skin-friction balance is unique in that the drag element is pre-cooled to the temperature of the surrounding tunnel wall by placing the coolant manifold (Fig. 5) in direct contact with the drag element before the data is taken. The temperature

of the drag element is monitored with two thermocouples mounted near the surface of the element. When the element reaches the desired temperature, a lever is actuated to release the manifold from the element. The servodevice is then turned on and data taken. The mass of the element is sufficiently large that the rate of the temperature rise is very small (about 0.5°C per second). The time required for the balance servodevice to go from the "no-load" condition to the "full-load" condition takes about 5 seconds.

The same liquid that is used to cool the tunnel test plate is usually used to cool the drag element. In tests performed in the NOL Boundary Layer Channel (Ref. 3) the balance was cooled with both water and liquid nitrogen. An element temperature range of 100°K to 345°K has been achieved.

Tunnel Installation

Figures 6 and 7 show the skin-friction balance installed in one of the instrumentation ports of the Boundary Layer Channel. It can be observed in Figure 6 that the balance extends through an outer wall of the wind tunnel and is mounted directly to the copper test plate of the Boundary Layer Channel. Both the mounting flange on the balance and the sensing element are manufactured from the same material, copper, as the tunnel wall. The tunnel is designed such that there is a vacuum between the back of the test plate and the outer wall structure. A flexible rubber diaphragm is used to seal the atmospheric pressure from the inner chamber. Because the test plate can be cooled with cryogenic fluids, the test plate undergoes severe thermal contractions whose movement, relative to the outside tunnel wall, can be as much as 0.6 cm. The diaphragm thus permits the balance, which is fixed to the test plate, to move relative to the outer tunnel wall.

Balance Calibration

The balance, because of the application in a vertical tunnel, is easily calibrated by attaching standard weights to the friction head with adhesive tape. A relation between the standard weight and the resulting voltages across the balance potentiometer is then obtained. A typical calibration curve is shown in Figure 8. It should be noted that corrections for the weight of the tape have already been subtracted in Figure 8.

Calibrations showed that the balance was sensitive to the pressure inside the balance which is equal to the static pressure of the flow. Tests also showed that the pressure effect is consistent and repeatable. A decrease in pressure always shifts the calibration curve downwards. No suitable explanation has been found for this calibration shift. A typical pressure calibration is shown in Figure 9.

In order to obtain the correct skin-friction shear stress, the following procedure was used:

1. Measure the shear force acting on the balance in counts, and the local flow static pressure.

2. Using the value of the measured pressure, determine the pressure correction.

3. Add the pressure correction to the test reading and use this sum and the load calibration curve to determine the corrected shear load acting on the element.

4. Divide the shear load by the area of the friction element to determine the local shear stress - the area of the element is 3.23 cm^2.

No temperature effect was found to exist when the balance was cooled with water. This included both the moderate heat-transfer case and the adiabatic wall case where the ratio of T_W/T_O was 0.68 and 1.0, respectively. A temperature effect was found when the balance was cooled with liquid nitrogen. The linearity of the calibration was not affected but only a zero shift took place. The primary cause of this temperature shift appears to come from the thermal expansions and contractions of the balance housing surrounding the flexures. Because of the non-uniformity of the temperature distributions in the balance housing, calibration of this temperature shift is very difficult. Small button heaters have been placed inside the balance housing near the flexures in order to maintain the housing temperature at a constant level. This has proven to be adequate but because of the non-uniform temperature distribution variation with time the heaters must be monitored and their output readjusted continuously. The balance housing is being redesigned out of thermal insulating materials to minimize or eliminate any temperature effects at cryogenic temperatures.

DISCUSSION OF DATA

Figures 10 and 11 show some typical results obtained with the skin-friction balance for low-heat-transfer conditions. The tests were performed in the NOL Boundary Layer Channel with zero-pressure gradient under the following conditions:

$M_\infty = 4.8$ $T_W/T_O = 0.68$

$p_O = 1$ to 10 atm $x = 2.134$ meters from throat

$T_O = 425°K$ $\frac{dP}{dx} = 0$

and with pressure gradient under the following conditions:

$M_\infty = 4.4$ $\qquad$ $T_w/T_o = 0.68$

$p_o = 1$ to 10 atm $\qquad$ $x = 1.775$ meters from throat

$T_o = 425°K$ $\qquad$ $\frac{dP}{dx} = 0.12 \frac{\text{mmHg}}{\text{cm}}$ to $1.22 \frac{\text{mmHg}}{\text{cm}}$

Shown in comparison are data taken with an uncooled balance obtained on loan from National Aeronautics and Space Administration (NASA), Ames. The NASA balance had a friction element which had an area of 1.265 cm^2. It can be seen that the results from the two balances are in good agreement. They agree within the stated two percent of full-scale accuracy of the NASA balance.

For the pressure gradient case no correction was made for the effect of pressure gradient across the friction head for either balance.

CONCLUSION

The NOL skin-friction balance has measured successfully skin friction under moderate heat-transfer and adiabatic wall conditions at a Mach number of 4.8 with and without pressure gradient. Shear forces ranging from 0.05 gm/cm^2 have been measured and higher ranges can be obtained by simply changing a coil spring. Tests have been made at low-heat-transfer conditions to compare results of the NOL balance with an uncooled balance on loan from NASA, Ames. The two balances agree with the stated two percent of full-scale accuracy of the NASA, Ames balance. Pressure effects on the balance cause a zero shift of the calibration line. This shift could be compensated for in the data reduction since the shift was repeatable. A temperature shift occured when the balance was cooled with liquid nitrogen. Small button heaters were placed on the balance housing to minimize this shift. This has proven to be adequate but tedious, thus the balance housing will be modified to eliminate the need for the button heaters.

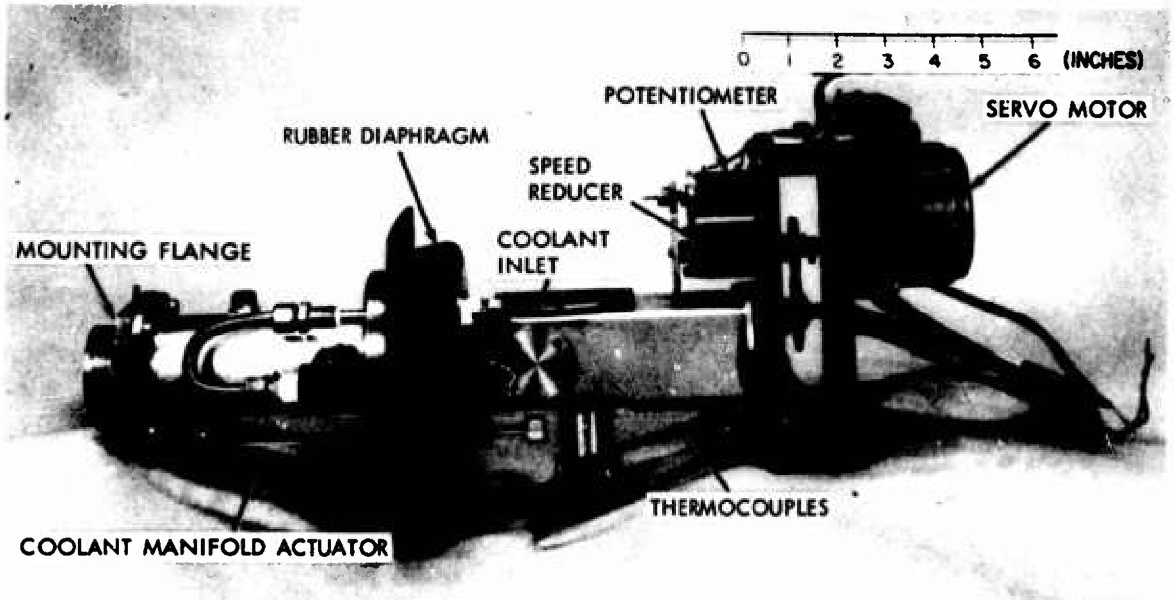

FIG. 1 SKIN-FRICTION BALANCE

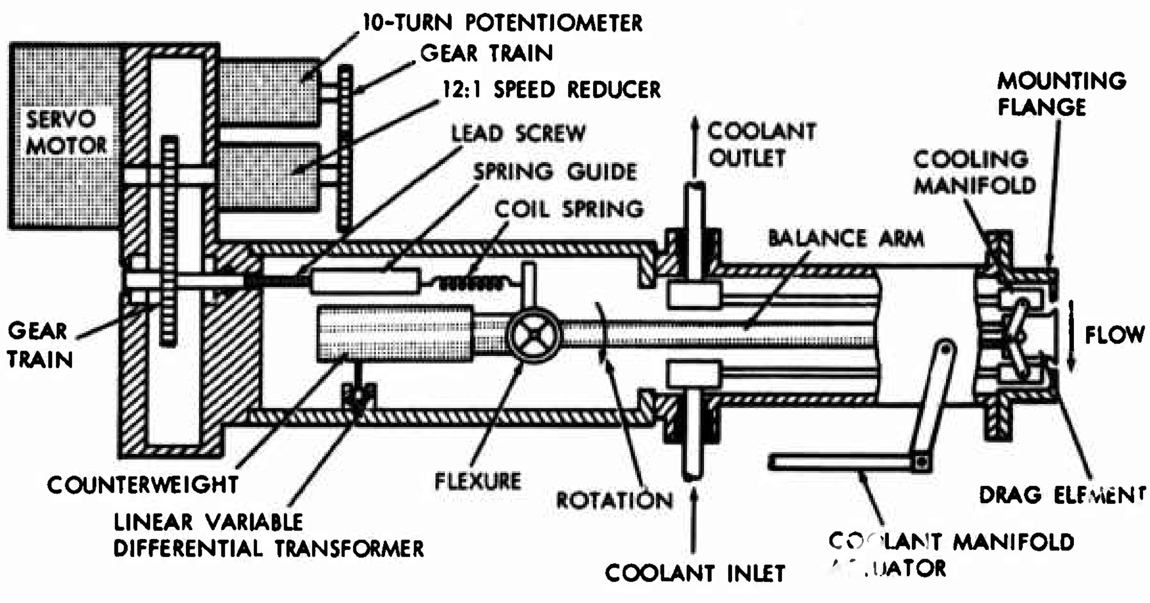

FIG. 2 BALANCE SCHEMATIC

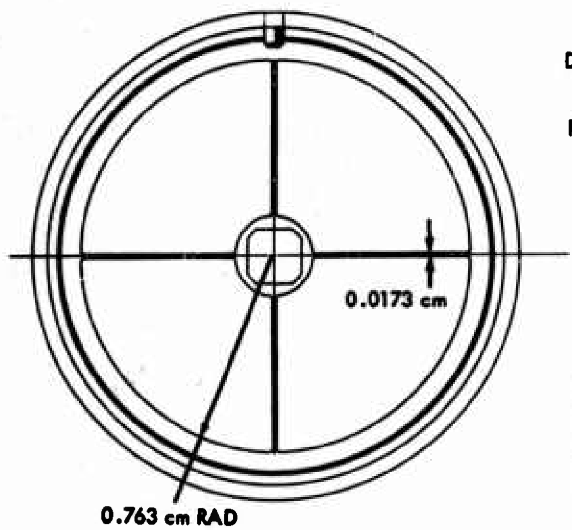

FIG. 3 FLEXURE CORE

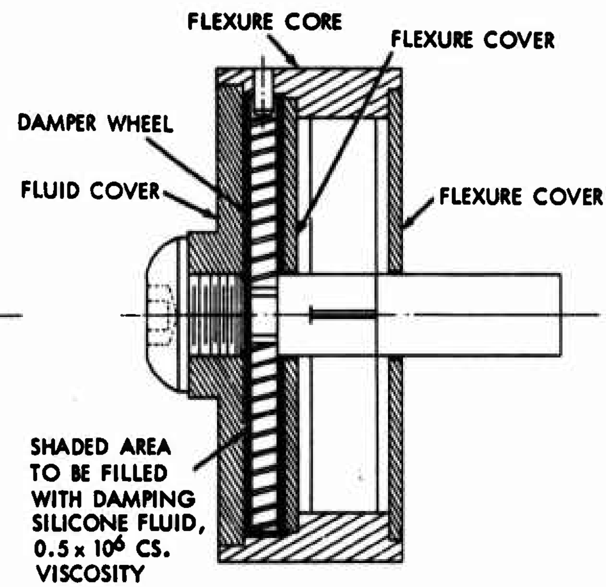

FIG. 4 FLEXURE

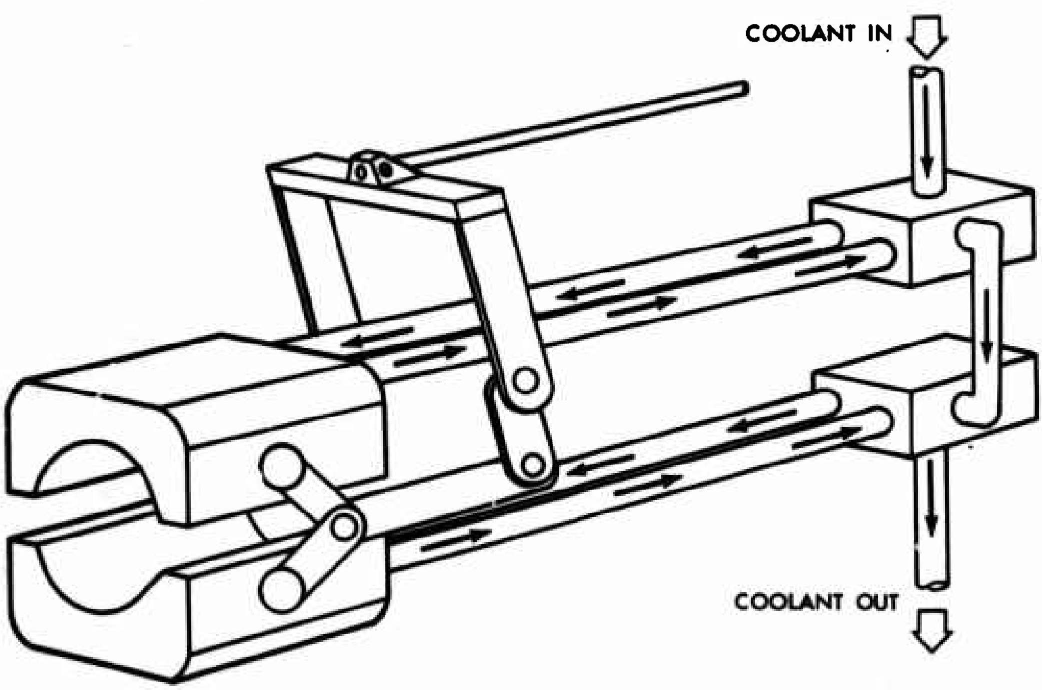

FIG. 5 COOLANT MANIFOLD

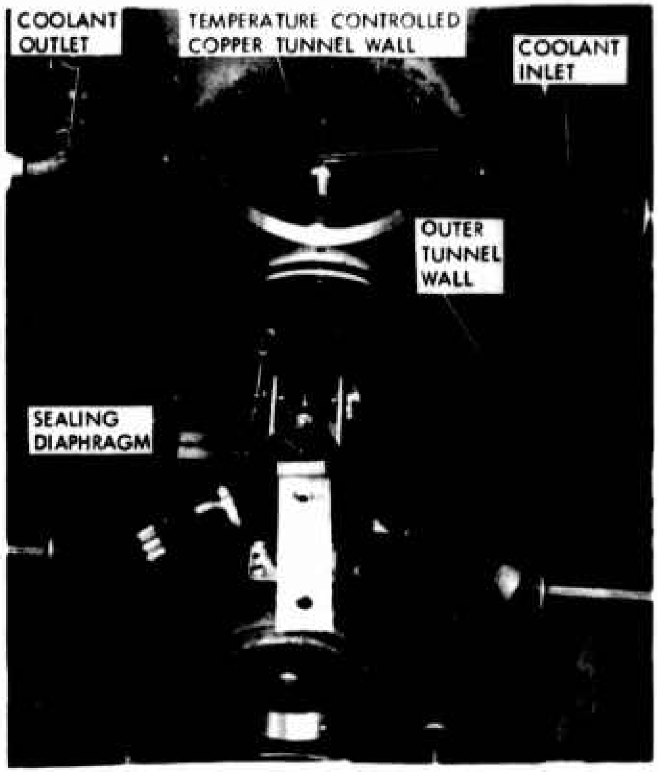

FIG. 6 TUNNEL INSTALLATION

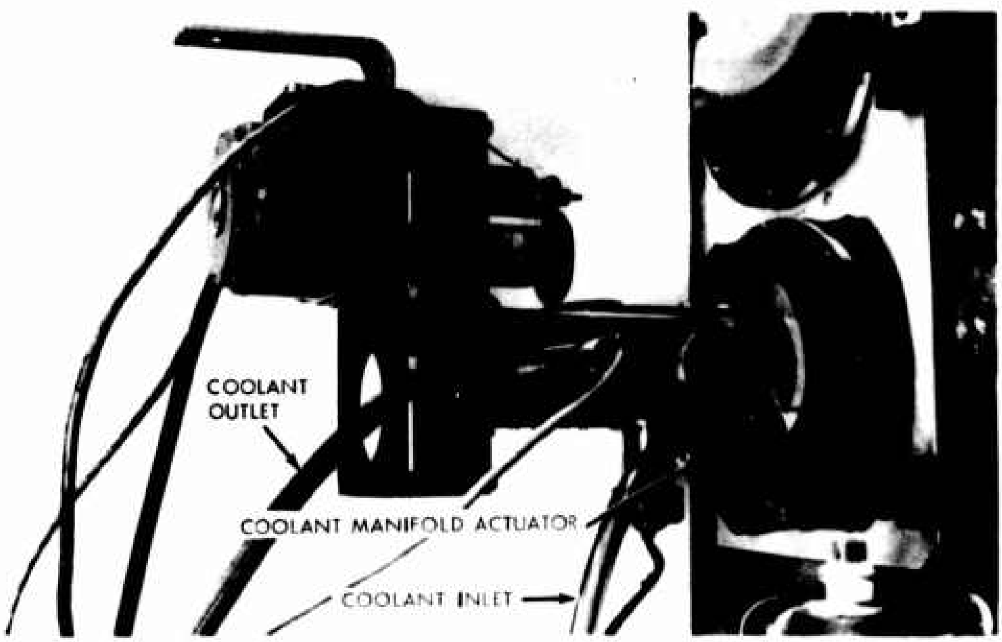

FIG. 7 BALANCE AFT SECTION

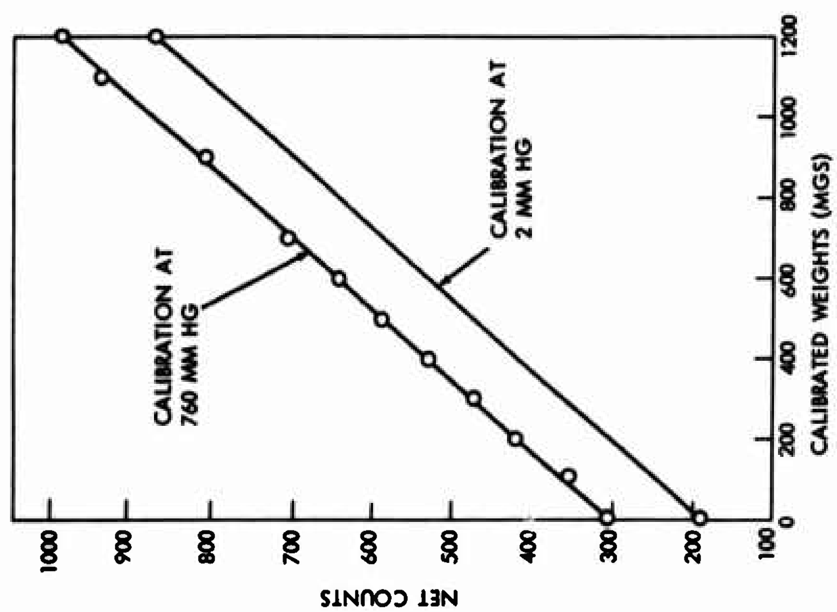

FIG. 8 TYPICAL CALIBRATION CURVE OF NOL BALANCE

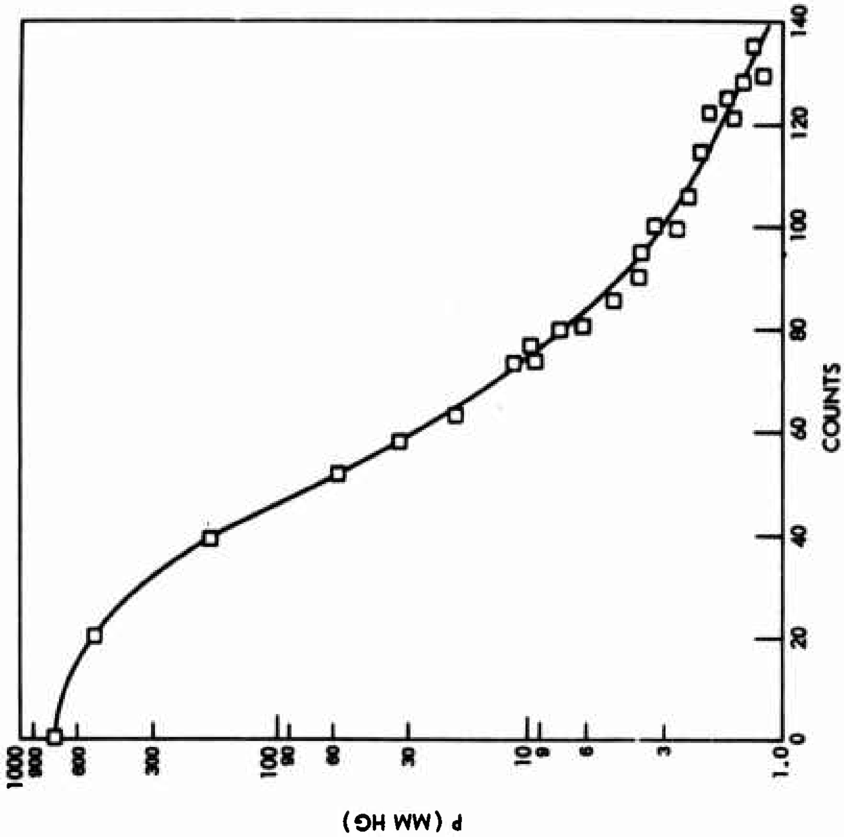

FIG. 9 PRESSURE CALIBRATION OF NOL BALANCE

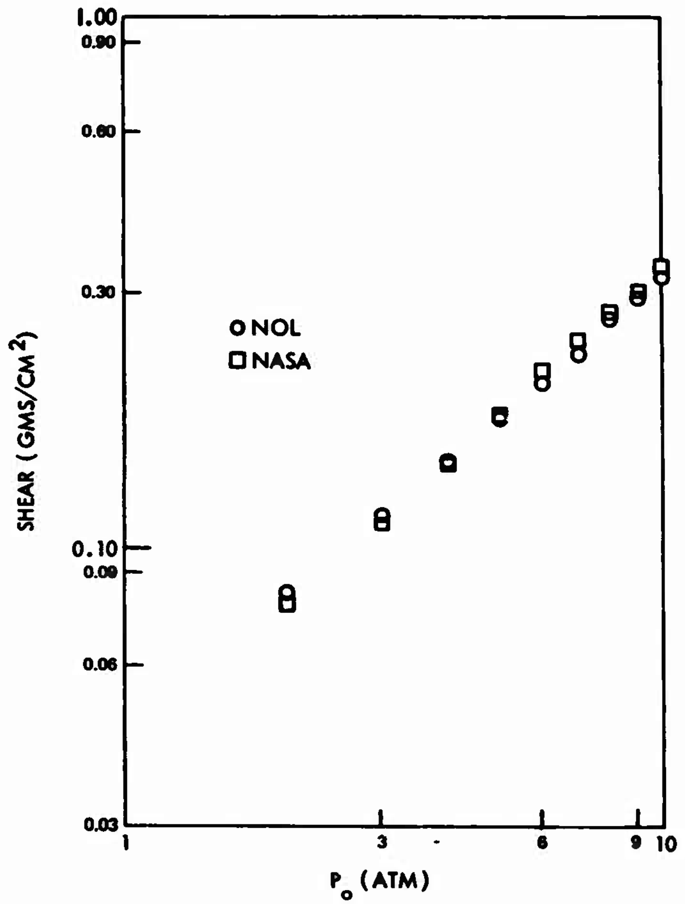

FIG. 10 COMPARISON OF NOL AND NASA BALANCES IN ZERO PRESSURE GRADIENT AT 2.134 METER STATION

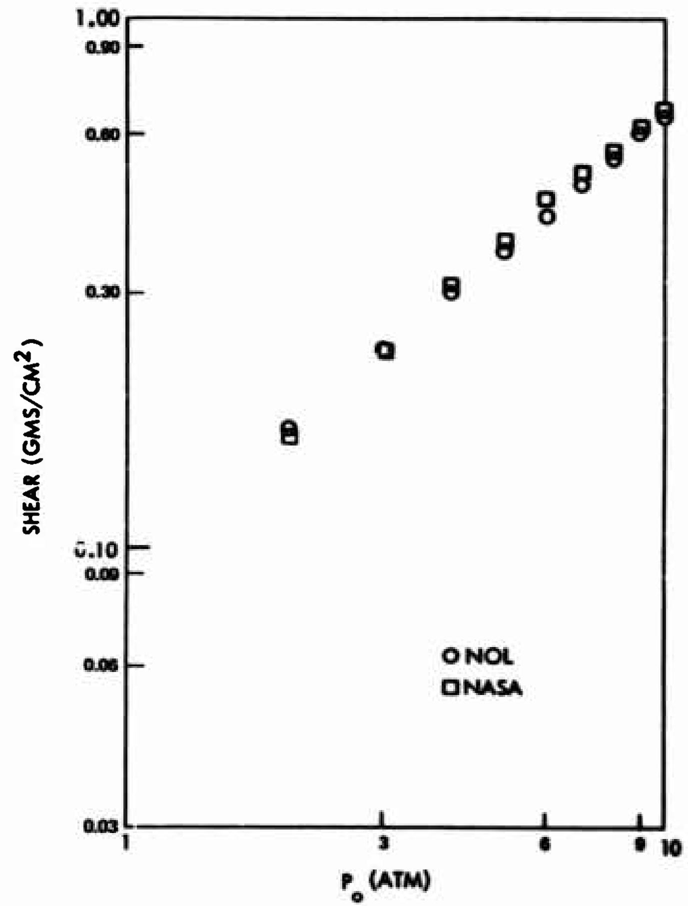

FIG. 11 COMPARISON OF NOL AND NASA BALANCES WITH PRESSURE GRADIENT AT 1.775 METER STATION

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